ALMA Memo 604

Detection and Mitigation of Radiation Induced Events in Integrated Circuits of the ALMA Baseline Correlator System

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Summary
The Cyclic Redundancy Check (CRC) circuit built in the Altera Stratix II FPGAs (90 nm technology, EP2S30 Altera FPGA) of the Tunable Filter Bank (TFB) cards in the ALMA baseline Correlator system and the TFB card design allow us, with the appropriate monitoring software, to estimate the Single Event Upset (SEU) rate observed in these devices at the 5050-m high ALMA site (AOS). SEUs are primarily due to the fast neutrons generated when the Cosmic Rays hit the Earth's atmospheric molecules. We have performed measurements at the AOS for a total test length of 930 hours in the years 2011 and 2012 during which we have monitored the 2048 Altera Stratix II FPGAs assembled on the 128 TFB cards of one baseline Correlator Quadrant. The measured SEU rate, 2.68 events per day and per Quadrant, implies a total rate of 10.72 SEUs per day for the complete 4-Quadrant Correlator system. We have tentatively shown that the SEU rate measured at the AOS was not affected by two Solar storms observed during our test period. The observed error rate compares well with the Altera predictions after the acceleration factor due to the site elevation and geographical location is included. The Failures In Time (FIT) rate is being dominated by errors in the configuration RAMs (of order 2500 FITS at sea level, 1 FIT = 1 failure in 10^9 hours). Prior to the final assembly of the last Quadrant of the baseline Correlator at the AOS, measurements were also performed at the Charlottesville integration site (nearly sea level) for all 2048 Altera FPGAs of the TFB cards. The measured rate was found to be 0.08 to 0.07 events per day for test lengths of 100 to 150 days, respectively. The SEU rate at the two sites varies roughly in proportion with the site elevation. The results obtained for the TFB card FPGAs show that the SEU rate in these devices (90 nm technology) is well above the SEU rate estimated for the baseline Correlator chips and other FPGAs (both with 250 nm technology) assembled on the Correlator cards. Therefore, measuring the SEU rate in the TFB cards provides a good estimate of the Cosmic Rays impact on the entire ALMA baseline Correlator system.

Mitigation of Cosmic Rays induced errors primarily consists in downloading the FPGA personalities ; the present work suggests that this should be performed several times a day when the full ALMA baseline Correlator is being operated. As a CRC error can be identified for each TFB card we also have the possibility to perform 'real time' recovery of the SEU events to improve the astronomical data quality. However, this approach still needs software development and prioritization. The ALMA baseline Correlator system can be considered as a 'neutrons detector' and long term recording of SEU events could usefully help to understand the impact of Cosmic Rays at the ALMA site in general.

1. Introduction and main objectives

Effects of Cosmic Rays on electronic devices are enhanced at high elevation terrestrial sites. They are a potential threat for the thousands of Altera and Xilinx Field Programmable Gate Arrays (FPGAs) as well as for all other integrated circuits used in the ALMA baseline Correlator system located at the 5050-m high ALMA site (AOS) to process 64 antennas of the ALMA array. The risk arises because of the very large number of digital circuits being used in this system and because of the low but finite probability that the casacde of neutrons generated in the upper terrestrial atmosphere by primary Cosmic Rays alter the personalities downloaded in the FPGAs. The most likely failure in the ALMA baseline Correlator is then a corruption of the FPGA personality resulting in a software error and a temporary loss of part of the ALMA science data.

In this memo, we first briefly recall the basic effects resulting from the interaction of the primary Cosmic Rays with the Earth's atmosphere and define the non destructive effects of Single Event Upsets (SEUs) on integrated circuits. Then, we concentrate on our main objectives :

(i) Measure with the appropriate software and the built-in redundancy check circuit in the Altera Stratix II FPGAs of the Tunable Filter Bank (TFB) cards the SEU rate observed at the ALMA high elevation site (AOS) ;

(ii) Compare the SEU rate at the high site with that at sea level for the same number of Altera FPGAs ;

(iii) Compare the SEU rate in the TFB Altera FPGAs with the error rate in other FPGAs and the ALMA1 Correlator chips ;

(iv) Discuss our results and how to mitigate Cosmic Rays induced errors.

Finally, we suggest to correlate the SEU measurements with other radiation measurements.

Effects of radiation on the ALMA baseline Correlator system were first discussed in [1] on the basis of the predicted vulnerability of thousands of Xilinx FPGAs used in the system. In the present memo we primarily propose to directly estimate in the baseline Correlator system environment, and at two widely different sites, the SEU rate thanks to dedicated monitoring routines and to the specific built-in circuitry available in the TFB card FPGAs. This is of interest not only as a general diagnosis tool to estimate the occurrence of anomalous events at the AOS but also for better operation of the baseline Correlator system. Our results should help to define a strategy to mitigate the impact of the Cosmic Rays in the ALMA baseline Correlator. SEU induced errors in other sub-systems of the ALMA Observatory using several FPGAs could perhaps be predicted as well, provided that the differences in the FPGA technologies (fabrication process or core voltage) are understood in terms of SEUs. We further note that another large number of Altera Stratix II FPGAs, similar to those in the TFB cards, are used in the receiver and transmitter modules of the current ALMA Digital Transmission System (1584 devices for 66 antennas ; one half located at the antennas and the other half in the Correlator room).

2. Cosmic Rays and Single Event Upsets in integrated circuits

2.1 Cosmic Rays and Earth's atmosphere

The Cosmic Rays of interest here are not the high energy protons or helium nuclei naturally produced in the outer space by cosmic sources (distant extragalactic nuclei, supernovae, etc.) or the Sun but the secondary particles and radiation produced by the primary Cosmic Rays when they enter the Earth's atmosphere. Protons, the most abundant primary particles, colliding with atmospheric molecules give rise to a Cosmic Ray 'air shower' of secondary particles whose energy depends on the energy of the primary particles. High and low energy neutrons are kicked out of the nuclei of the atmospheric molecules during this process while gamma rays resulting from the decay of neutral pions are produced simultaneously. The neutron production process is fully random. (Charged pions rapidly decay to muons and other particles which supposedly are not of interest in generating SEUs.)

Both neutron and gamma ray dose rates were measured near the AOS site and at lower elevations with dedicated dosimeters and neutron *rem* counters (see reference [2] and Sect. 5.2). It was found that the measured particles and radiation doses are more pronounced with altitude for the neutrons than for the gamma rays.

2.2 Single Event Upsets

A Single Event Upset (SEU) is a non destructive effect due to radiation, fast atmospheric neutrons or ionized energetic particles impinging on an electronic device or a semi-conductor memory. The net result is a change of state in an integrated circuit or a software error. An SEU may toggle one of the flip-flops in a microcircuit resulting in a functional error, or may trigger bit flips in a memory or a register. Once detected, software errors can simply be erased by reloading the content of a memory or the circuit registers. Radiations and Cosmic Rays have long been recognized to be a potential source of software errors in RAMs (see e.g. [3] and [4]).

SEUs are expected to become more frequent at higher elevations due to the enhanced effect of fast neutrons generated from the interaction of primary Cosmic Rays with the terrestrial atmosphere. These neutrons when they hit a silicon nucleus give rise to various fragments and electrical charges which may upset an electronic device or a volatile memory. SEUs could also be due to the Alpha particles generated by the radiaoctive decay of natural isotopes present in the device package or in impurities. This source of SEUs should be weak and is well mastered by appropriate packaging of commercial FPGAs ; it is notelevation-dependent.

2.3 Other events

At the ALMA site, contrary to space crafts or satellites exposed to energetic primary Cosmic Rays or Solar activity, destructive events such as ‘latchups’ are not expected a priori. However, we suspect that such an event was observed by us (see Section 4.4). In addition, single event transients could perhaps trigger voltage pulses (or glitches) propagating through the I/O pins of microcircuits. To protect the baseline Correlator system from such problems or malfunctions the system watches for high currents in the most critical places of the Correlator (see Section 5.1).

3. Measuring SEUs in the Correlator filter cards

3.1 Cyclic Redundancy Check in TFB card FPGAs

One of the types of boards in the Correlator, the Tunable Filter Bank (TFB) board, was designed with the capability of detecting errors in its FPGA personalities and reporting them to higher level software. These types of errors are predominantly caused by SEUs. Since there are 512 TFBs in the Correlator, they constitute an effective SEU detector. Some details of the implementation of this detection mechanism are included in the following pargraphs.

The FPGA used in the TFB cards is the Stratix II EP2S30 from Altera (34000 Logic Elements, 90 nanometer logic process). It provides a Cyclic Redundancy Check (CRC) built-in circuit which routinely checks for possible soft errors in the configuration memory while the device is being used (see [5]). Each FPGA has a dedicated error output line which is enabled at the compilation stage. Therefore, only one external pin has to be monitored for CRC errors. A small programmable logic device (CPLD) assembled on the TFB card is used to monitor all error lines in the matrix of 4x4 Altera Stratix II chips on each board. These 16 lines are ‘OR-ed’ and one output line is sent to another CPLD, CPLD2, which is primarily used to download the FPGA personality. There is only one memory error line for all 16 FPGAs on one TFB board. Note that with this design and for observations not requiring all FPGAs (our strategy is to operate those unused FPGAs in low power mode) it is not possible to identify if an SEU occurs in an FPGA that is not being actively used.

When a soft error occurs (bit 7 of the CPLD2 monitor register is asserted) the green led on the TFB card front panel is switched ‘off’ and the red led is ‘on’. However, the red led can be ‘on’ if the digital filter Delay Locked Loop (DLL) or the delay chip DLL at the TFB input is unlocked, or if the 3.3V supply is not nominal ; no DLL or 3.3V supply means no filtering functionality.

The time required for each CRC calculation depends on the Altera product and the error detection clock frequency can be specified in the Quartus II software. In our case we use 390 kHz corresponding to the minimum error detection frequency. The CRC calculation time for each Stratix II device assembled on the TFB card is around 2.8 seconds ; we thus get around 30000 samples after one day CRC monitoring.

In addition to the 16 lines OR-ed to monitor SEU events, a seventeenth line is available to check the contents of the RAMs used in the filter design and the DDS mixer block of the TFB filter (an error could occur in the DDS sine table for example). The memory blocks support parity bits to check the memory contents but this possibility is not implemented in our current firmware as it requires to use additional FPGA logic elements. We anticipate that flagging the data on the basis of corrupted memory blocks in the TFB card is not desirable. There is much spare logic available in our design, however, and checking the memory contents would be possible if that would be required.

3.2 Impact of neutrons on Altera products, Failures In Time (FIT) rate

Accelerated soft error testing and SEU FIT rate measurements or estimates (1 FIT = 1 failure in 10^9 hours) have been made by Altera for their products when they are submitted to both terrestrial neutrons generated by Cosmic Rays and Alpha particles generated by package materials. Although these data are not public, confidential information was passed to us in 2005 [6] at a time where the technology to be adopted for the new, flexible version, of the ALMA digital filter card was still under discussion between the University of Bordeaux group and the Altera engineers. The relative impact of neutrons on the Stratix I (130 nm), Stratix II (90 nm) and HardCopy I products were compared and it was concluded that the more powerful Stratix II EP2S30 FPGA would not be much more affected than the Stratix I products at sites above 5000 to 10000 feet. (The FIT rate for the HardCopy I version is more than one order of magnitude below the EP2S30 FIT rate but this version was discarded because it did not offer the ability to reprogram our filter design and because we had demonstrated that the Stratix II-based filter card design could dissipate little power.)

Following our own SEU rate measurements made in 2011 and 2012 in the baseline Correlator system (see Section 4) further SEU information was provided to us by Altera for their 90 nm products [7]. The various components of the Altera FPGA circuits contribute to the net FIT rate. The configuration RAM (CRAM) errors dominate while errors from Logic Elements or I/O registers are much smaller and the user memory errors are detectable and correctable. For the EP2S30 FPGA the CRAM errors estimated by Altera are 2506 and 737 FITs at sea level for the neutron and Alpha particles contributions, respectively ; these numbers will be used in Sect. 4.1 for comparison with our measurements.

3.3 Conditions and firmware to identify SEU events at the AOS and sea level site

The impact of Cosmic Rays on integrated circuits at the ALMA high site is largely unknown and although Altera FIT predictions exist it is important to check their FIT predictions and to monitor the actual number of anomalous events occurring in the ALMA baseline Correlator system environment. This system consist of 4 Quadrants of digital electronics which were delivered sequentially to the ALMA observatory. The Correlator team was in a most favourable situation to perform SEU tests in two widely different sites when the third Quadrant was installed at the AOS but unused for science or engineering tasks and the fourth Quadrant was still under test at the NRAO technical building in Charlottesville (nearly at sea level) before delivery to the AOS. Each Quadrant includes a total of 128 TFB cards with a total of 2048 Altera FPGAs. This number is rather high and, provided that error monitoring is performed over a long enough period of time, a sensible SEU rate can then be estimated and variations of this rate at the two different sites can be observed.

The key elements in such measurements are the CRC circuit and error check logic implemented according to the scheme described in Section 3.1. Our design thus allows us to remotely monitor errors due to SEU events. The Station Control Card (SCC) must periodically monitor Bit 7 of the CPLD2 monitor register on the TFB card to be informed of eventual CRC errors. Infrequent inquiries, of the order of a few seconds as suggested by the time required for the CRC calculation are sufficient to check for errors. This information can be passed to the Correlator Control Computer which periodically monitors various parameters across the baseline Correlator system. Dating the errors is not mandatory but, the CRC errors being random by nature and infrequent, the day and month of the errors should be recorded as well as the total duration of the monitoring period.

In practice, for remote semi-manual SEU measurements in the third and fourth Quadrants, the Correlator team used a dedicated command issued from the ‘engineering port’ in the Correlator ‘back-end’. This command allows us to remotely and simultaneously check for possible SEUs in all TFB cards of a Quadrant. When the SEU error flag was present, additional checks were made to exclude other sources of errors (see next Section).

4. SEU statistics in the ALMA baseline Correlator system and observed radiation effects

4.1 SEU measurements in the TFB cards at the AOS and Charlottesville

SEU measurements were performed in the third Quadrant at the AOS by checking the SEU error flag according to the procedure outlined above. In addition to the error flag check, a number of other checks were made to decide if the error event could be kept for our SEU statistics. These checks included monitoring the power consumption, Delay Locked Loop error status (with respect to reference clock), local bus connection and the TFB current/voltage reading. At the same time, auto-correlation spectra were acquired in the ‘Frequency Division Mode’ for 2 GHz bandwidth and dual polarization mode (all TFB cards in one Correlator Quadrant are used in this operating mode) in order to check for undesired spectral artefacts or eventual functionality problems. We had to discard from our statistics a few suspicious cases where for an apparent radiation error in one particular TFB card we had spectral spikes in all auto-correlation spectra. Data were acquired during the period 21 October 2011 to 1 September 2012. The monthly and total duration of our monitoring is shown in Table 1.

Table 1. SEU monitoring in the 3rd Quadrant of the ALMA baseline Correlator at the AOS (5050-m elevation)

Month / Year	Test duration (hours)	Observed radiation events	Radiation events rate (events/day)
Oct 2011	35.717	4	2.7
Nov	156.217	14	2.15
Dec	101.000	13	3.1
Jan 2012	189.600	22	2.8
Mar	48.283	5	2.5
Apr	55.000	6	2.6
May	58.067	6	2.5
Jun	61.633	5	2.0
Jul	107.350	14	3.1
Aug	104.850	13	3.0
Sept	12.300	2	3.9
Grand Total	930.017=***38.751 days***	***104***	***2.68/day***

The monthly duration of the SEU monitoring was quite irregular and varied from 35-50 hours up to nearly 190 hours. Nevertheless, the observed monthly rate of events (except for September with only 12 hours data monitoring) does not fluctuate much around the total average of 2.68 events per day (104 events for 38.751 day monitoring). Although the accumulated data varies significantly from one month to another these results tend to show that there is no systematic change in the SEU rate from Oct 2011 to Sept 2012. Our monitoring during 38.751 days of of 2048 FPGAs in the third Quadrant implies that about 10.7 SEUs/day should be expected at the AOS across all TFB cards in the full baseline Correlator system.

Our measurements can be compared with the Altera predictions. Restricting the analysis to CRAM errors (see Section 3.2) and accounting for the FIT rate acceleration factor of 17.46 (due to the ALMA geographical position and elevation) we obtain 2.18 events/day for 2048 Altera EP2S30 devices in one single Quadrant. This prediction must be considered as a minimum value since other sources of events are not included (Solar activity for instance). It is reasonably close to the actual measurements for one Quadrant (2.68 events/day, Table 1).

Similar measurement procedures were used for the fourth Quadrant of the ALMA Correlator to estimate the SEU rate at Charlottesville before it was moved to Chile. Measurements began in March 2011 and lasted longer than at the AOS as required for a 130-m elevation site where fewer events are expected. The measured rates are 0.08 and 0.073 SEU/day for test lengths of 97.7 and 149.85 days, respectively (Table 2).

We note that the ratio of the SEU rates measured at the 5050-m and 130-m sites in one Quadrant, (2.68 events/day)/(0.08 events/day) = 33.5 or (2.68 events/day)/(0.073 events/day) = 36.7, depending on using 0.08 or 0.073 SEU/day per Quadrant at Charlottesville (Table 2), is close to the sites elevation ratio of 5050/130 = 39. As expected, the neutron flux impacting the integrated circuits increases with elevation and our measurements reflect this trend. More generally, this flux depends on the site latitude as well. The fact that the elevation ratio of 39 is close to the SEU rate ratio derived above (33.5 or 36.7) is probably accidental[8].

Table 2. SEU monitoring in the 4th and 3rd Quadrants of the ALMA baseline Correlator at Charlottesville (130-m elevation) and the AOS (5050-m elevation), respectively. Prediction for the full 4-Quadrant system at the AOS is shown in the last row

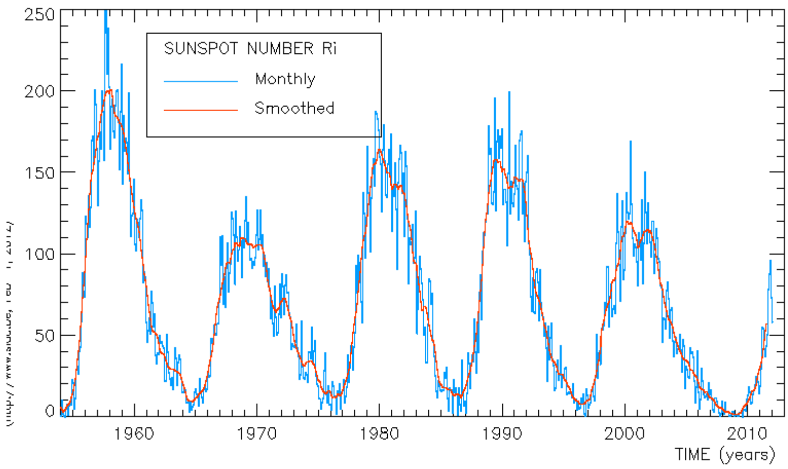
Correlator Quadrant / Site	Test duration (days)	Elevation (m)	Radiation events rate (events/day)
1 Quadrant *Charlottesville, VA* 2048 FPGAs monitored [a)]	97.7 149.85	130 130	0.08 0.073
1 Quadrant *AOS, Chile* 2048 FPGAs monitored [a)]	38.751	5050	2.68
4 Quadrants *AOS, Chile*	(4-quadrant extrapolation)	5050	10.72

[a)] 16 Stratix II EP2S30 devices from Altera (90 nm technology) are assembled on each TFB card. There are 128 TFB cards per Correlator Quadrant.

4.2 SEU rate and Solar activity

Because the number of radiation events per day in one Quadrant and in the full ALMA baseline Correlator system is rather high (Tables 1 and 2) it is worth investigating whether there might be some relationship with the Solar activity. The 'normal' Solar activity can be measured in terms of the Sunspot number (Fig. 1). It is anti-correlated with the neutron counts measured on the Earth because the Sun's magnetic field is stronger around the Sunspot maximum and protects us from the Cosmic Rays. The period from about 2010 to about 2015 was favourable since the Sunspot number increased according to the undecenal Solar cycle (the minimum was reached in 2009, Fig. 1). However, we have observed events at the AOS in the 2011-2012 period which was perhaps still too close to the Sunspot number minimum. The overall Solar picture is much more complex than the image provided from 'normal' activity. Solar wind streams, shocks and enhanced magnetic field activity may help to repel the Cosmic Rays while Solar flares are frequent and may inject fast neutrons and ionized particles thus affecting the average neutron counts at high elevation sites. Two significant Solar events were observed during our SEU measurements at the AOS. A large Solar eruption was observed around Christmas 2011 and the strongest Solar storm observed since 2005 was recorded in January 2012. Despite our SEU data base is relatively small we have counted the events in different monthly bins (Table 1) but could not find any significant deviation from the average 2.7 SEUs per day and per Quadrant in relation with these Solar events.

Nevertheless, Solar Energetic Particles (SEP) generated by Solar flares or shocks associated with Coronal mass ejections can affect our average SEU rate measurements. Typical SEPs (<100 MeV for protons) impact the upper terrestrial atmosphere only but the Solar proton spectra can reach the 1-10 GeV domain where cascades of particles can be induced throughout the Earth's atmosphere. It would be useful to measure at the AOS the local Cosmic Ray increases during such Ground Level Enhancement events [8].



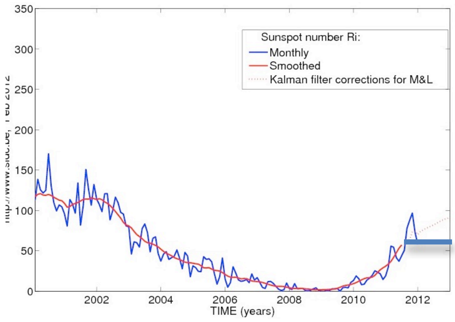


Fig. 1. Sunspot number in the period 1960 to 2012 (top). Enlargement of Sunspot evolution in the years 2002 to 2012 (bottom left). The blue horizontal bar shows the approximate duration of SEU monitoring at the AOS for the period 2011-2012

4.3 SEU rate in full ALMA baseline Correlator system

The average SEU rate expected at the AOS for the 8192 Altera FPGAs of the entire filtering sub-system (512 TFB cards) is relatively high, 2.68 events/day x 4 = 10.72 events/day, and must be compared with expectations for the other devices in the baseline Correlator system. As for the TFB FPGAs neutrons and radiations randomly affect the 32768 Correlator chips and the thousands of Xilinx chips assembled on the 512 correlation cards of the ALMA Correlator. Because the smallest Xilinx chip already has four times the number of flip-flops in a Correlator chip, the SEU risk is much higher in the Xilinx FPGAs than in the Correlator ASICs where it can be neglected (see [1]). The 250 nm technology used in the ALMA1 correlator chip is also less susceptible to the effects of radiations than the 180 nm technology used in the Xilinx FPGAs and, even if one event would affect one lag flip-flop among the numerous flip-flops in the 4096 lags of each ALMA1 chip, the error would be for a single 16 msec integration time of the Correlator. There is no CRC circuit available in the Xilinx chips used in the ALMA baseline Correlator system and we rely on the Xilinx predictions and estimates made in [1]. In the final Correlator design where the filtering function is implemeneted in the TFB cards, the mean time between two SEU events in the Xilinx chips on all Correlator cards is predicted to be 716 hours at the AOS. This is about one event every 30 days to be compared to 10-11 events per day in the 512 TFB cards.

Clearly, the 8192 Altera chips in the TFB cards with more recent 90 nm technology are more susceptible to SEU errors than other FPGA devices or the Correlator chips in the entire baseline Correlator system.

4.4 Observed radiation effects in TFB cards and mitigation

During the course of the ALMA Correlator test tasks at the AOS 4 TFB card failures were observed and identified with 4 different FPGA failures. Unfortunately the SEU monitoring routine was not active at that time but when the incriminated FPGAs were removed and replaced the functionality of the TFB card was fully restored. In one case, however, some FPGA balls were burnt and the TFB board was damaged (Fig. 2). We suspect that the observed apparent short-circuits on the 1.2 V supply were due either to high SEU rates or, in one case, to Cosmic Ray induced latchups. To mitigate potential destructive effects the Quadrant Correlator Computer (QCC) monitors the TFB 1.2V regulator currents to eventually shutdown the system beyond an adopted limit. Since the current limit in the 1.2V DC-DC converter has been lowered by 20% no QCC shutdown has been recorded because of destructive events or high currents in the TFB cards. (The QCC monitoring loop operates at a low rate and cannot compete against the duration of Cosmic Ray induced events in ICs ; however, it helps in avoiding the possible deterioration of a board.)

These reported failures demonstrate the potential destructive impact of radiations at the AOS and strengthen the interest of implementing an SEU monitoring policy.

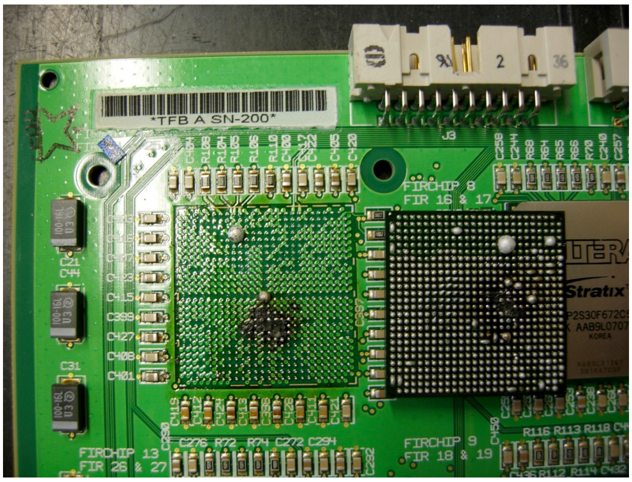


Fig. 2. Extreme case where TFB printed circuit board and removed FPGA are both damaged (burnt area on both printed circuit board and FPGA balls) due to suspected Cosmic Ray induced latch-up

5. SEU errors mitigation and data integrity, Other radiations measurements

5.1 Mitigation of SEU induced errors and Correlator operation

To mitigate the effects of SEU events it was proposed initially to download daily all the FPGA personalities (see [1]). The present work suggests that much more frequent reconfigurations would be desirable for the FPGAs in the TFB cards when the full baseline Correlator system is at work. This would enhance the astronomical data integrity.

The exact procedure to follow after an SEU event has been detected must still be worked out. The most conservative approach consists in downloading the FPGA configuration in all TFB cards and/or downloading all FPGA personalities for all devices in the baseline Correlator system when there are no observations or during large antenna slews. This is feasible because downloading the FPGA personalities is performed quickly compared to the approximate 30 seconds needed to reset the entire baseline Correlator system. If reloading the FPGA personalities does not correct an apparent SEU-induced error reported to the Station Control Card (SCC), our design allows us to identify the faulty TFB card for a later cure of the fault. Preliminary, internal discussions have suggested that the following sequence might be applicable for 'real-time' error flagging, mitigation and analysis. When the SCC finds an SEU error while monitoring various baseline Correlator parameters (about every 10 seconds), it reloads the faulty TFB card personality and the registers needed to make it operational. When the CCC receives the SEU error message it logs the SEU event so that downstream data processing can take it into account. SEU events may be recorded in a dedicated SEU data base for further analysis. In addition, since the QCC watches for high TFB currents these errors could be cross-checked with the SEU error data base to search for possible Cosmic Ray induced events in relation with high currents. This approach requires new software development and software development prioritization to be efficiently implemented in the ALMA Observatory.

Although not all TFB cards will be used for all types of observations, 'real-time' recovery of SEU events in the TFB cards is highly desirable to optimize the astronomical data integrity. Long term SEU monitoring and analysis would also be useful to precisely investigate the possible impact of cumulated radiation doses on integrated circuits and FPGAs at the AOS. Such a 'natural' long term degradation is perhaps acceptable but it is unknown. We further note that SEU monitoring should be combined with other error tracking approaches to regularly optimize the system integrity. For instance, when there are no observing sessions or between observing runs, pseudo-random data can be used to mimic observations and check the entire baseline Correlator system. Or, when observations do not use the entire baseline Correlator system, partial system checks could also be performed in parallel.

5.2 The ALMA baseline Correlator as a 'neutrons detector' and comparison with other measurements

This work demonstrates that the SEUs observed in the ALMA baseline Correlator system at the AOS are not negligible. In other words, the ALMA baseline Correlator can be considered as a 'neutrons detector' when the CRC circuit and SEU monitoring routines are active. We advocate that recognizing this 'new property' of the baseline Correlator is highly desirable not only for its integrity but also to contribute in an evaluation of the impact of radiations at the AOS. Enhanced exposure to ionized particles and neutrons at the ALMA site was clearly demonstarted in [2]. The dose rates of the ionizing components was found to be around 3 times higher at Pampa La Bola (4800-m, near AOS site) than in Santiago (500-m elevation) and the measured neutron dose rate was greatly enhanced at Pampa La Bola. A higher exposure at Pampa La Bola than at other sites with similar elevations was tentatively explained by the proximity of the Chilean site to the South Atlantic Anomaly (a region exposed to an enhanced flux of particles because of the weakness of the Earth's magnetic field).

More simply, we suggest that with appropriately calibrated and dedicated equipment (as in [2]), it would be possible to measure the exposure to neutron particles and gamma rays within the Correlator room and to search for any correlation with the SEU induced errors in the ALMA baseline Correlator system. If such a correlation would be established, then the baseline Correlator system alone could be consisdered as a neutron dose measurement machine. In addition to bringing newer information to the very first results presented in [2], this could valuably help to characterize the ALMA site and perhaps contribute to estimate the effects of human exposure to neutrons and radiations.

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